Handling Commercial, Operational and Technical Uncertainty in Early Stage Offshore Ship Design

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***Abstract*—In this paper, we assess state-of-the-art methods for handling aspects of technical, commercial and operational uncertainty in the early stages of offshore ship design. Uncertainty affects the lifecycle performance of a ship in a complex manner, which is difficult to assess in the early design process. We approach this problem by decomposing uncertainty into technical, commercial and operational aspects, and investigate how it can be identified, modelled and handled. Methods discussed include design structure matrix, tradespace exploration and evaluation methods, real options theory, stochastic optimization, and system dynamics. Strategies for handling uncertainty discussed include margins, and specific system lifecycle properties "-ilities". We argue that a decomposition of uncertainty facilitates the use of current methods and approaches for decision-making in early stage ship design.**

Keywords — System Engineering, Ship Design, Uncertainty, Ship Life Cycle, Flexibility, Decision-Making

I. INTRODUCTION

Ship design development is a complex decision-making process [1] where the designer has to make compromises among the design variables to come up with a fully operational system. The vessel as an operational system is designed and improved to perform the desired operations within the considered initial operational and commercial boundary conditions - solution space. There always exists significant uncertainty in the ship design process and the future lifecycle [1]. Designers and owners should keep in mind that the vessel has to keep acceptable levels of performance over its entire life, as needs and expectations change, and the technical capabilities deteriorate. Further, critical decisions are often made without proper control of consequences of the decision-making process, and in some cases, without even a clear reason behind it [1].

As Suh [2] well describes, a final design cannot be better than the set of functional requirements that it was created to satisfy. A vessel design developed from a weak specification is not expected to have superior performance. Understanding the objectives of design early on becomes important, as signified by discussions on *Design for X* [3], where "X" represent specific system lifecycle properties, or "-ilities"[4]. Many "-ilities" characterize strategies for designing capabilities for handling future uncertainty into the system. For example, changeability [4] refers to the ability of the system to alter its form and function for the future.

To support the decision-making process in ship design, and to guide the designer in making better compromised decisions, Ulstein has developed and tested different vessel performance perspectives based on *Design for X*: Design for Efficiency, Design for Effectiveness and Design for Efficacy [5] [1]. This paper focuses on the *Design for Efficiency* perspective, which relates to technical, operational and commercial aspects. We aim at improving the current uncertainty handling processes by decomposing uncertainty into commercial, operational and technical domains, in order to understand better how it will affect the lifecycle performance. Ulstein and Brett [1] define the three aspects of the *Design for Efficiency* perspective:

- Technical refers to all factors/articles/systems that influence the intrinsic effectiveness of the vessel over its project life-cycle and that affects the design and construction process of the vessel.
- Operational refers to all factors/articles/systems that influence the performance of different missions, for which the vessel is designed and set to do, improving operational conditions.
- Commercial refers to all factors/articles/systems that influence the valuation, preferences and exploitation of the vessel during its operational lifetime and increases the returns of the investment.

One can argue to some degree that for a commercial vessel, all operational and technical factors of interest indirectly affect the commercial aspects. Some factors can also overlap between the different aspects. A recent example in the shipping industry is the introduction of emission control areas (ECAs). This regulation, based on the limitation of emission levels of ships when sailing in certain regions affects the three performance aspects of the vessel. However, in terms of managing complexity we aim at differentiating between them in this paper. Seeing the clear need of integrating commercial, operational and technical aspects in early stage of ship design, we argue that a combination of finance, management and systems theory would better handle the complexities of ship design under uncertainty (Fig. 1). An alternative taxonomy is given by Erikstad and Rehn [6], grouping uncertainty as emerging from economic, technological, regulatory, and physical sources.

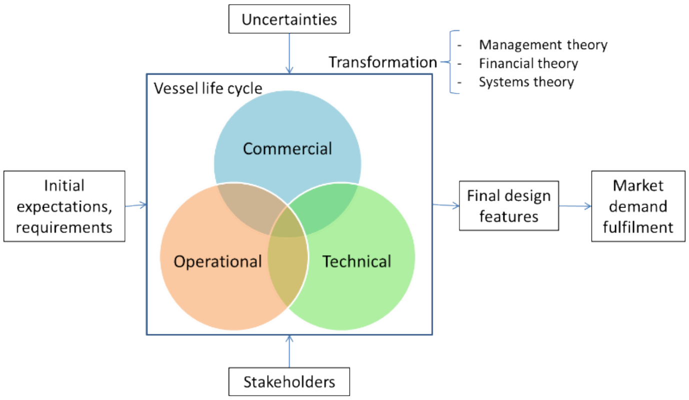

Fig. 1. System model adapted to ship design. Adapted from [7].

Offshore ship design has been focused on state-of-the-art vessels with the highest technical performance, without explicitly considering the operational and commercial risks. Having the largest crane, highest bollard pull and fastest vessel have been the principal conditions in the decision-making processes. Today, a low oil price market leads to a stronger focus on cost reduction, resulting in a more pragmatic view on what is a "good enough" coverage of technicalities. The history has shown that neither a pure technical view nor a commercial-operational view seem to be effective.

II. UNCERTAINTY IN EARLY STAGE SHIP DESIGN

Uncertainty can arise from both endogenous and exogenous sources [8]. Decision-makers can actively manage endogenous uncertainty, and examples are propulsion power, steel weight, deadweight, painting area, vessel parameters that the designer is not 100% certain about until the vessel performs, for example its sea trials. Exogenous uncertainties are external and independent of actions by decision-makers; these can for example be market rates, fuel prices, new regulations or accidents. Combinations of exogenous and endogenous uncertainties may also arise, like shipbuilding schedule and costs. In this paper we will focus on both types.

A. Commercial aspects

When ship-owners order ships, they aim at positioning their investments to satisfy a need in a market, where they essentially will earn a return on their investments, by operating, chartering or selling them. Therefore, when looking at an offshore ship as an investment from the key stakeholder's perspective, the commercial aspects of the vessel quickly becomes central: What is the vessel intended for? While market uncertainty often is related to the risk of losing money because of a negative market development, there should also be emphasis on the potential upside opportunities that may arise from uncertainty [9].

Uncertainties in commercial aspects of offshore ship design can principally be structured based on how they affect the economic viability of the project. One could reduce the complexity by assessing what, how and how much, design factors affect the cash flow of the vessel, revenue and costs [10]. Revenue generating factors relate to cargo capacity, productivity and freight rates, and cost driving factors are mainly capital expenses (CAPEX), operational expenses (OPEX) and voyage expenses (VOYEX). What is of interest at this stage is to identify the most important factors that influence the commercial performance of the vessel, and understand how those are affected by uncertain factors. The single most important factor in the offshore shipping market is most probably the oil price, which as of 2016 has proven to be highly stochastic. The stochasticity of the oil price affects both revenue generating factors, with the market rates, and costs – VOYEX, mainly through the fuel costs. Technical and operational uncertainty will often influence the commercial performance of the vessel by affecting the costs and earning capability. In the end, the objective is most often a commercial one; to generate value for the ship owner.

B. Operational aspects:

Most vessels are designed with a specific operational profile in mind, with regards to for example speed or operability in a given sea state. Once the vessel is put into its trade we need to ask whether the actual operational performance fits the intended operational performance.

The discussion of operational aspects of uncertainty can relate to the sea states the vessel will meet. Operability in harsh weather is an important factor for the design. Regions such as the North Sea require higher propulsion power than for example South China Sea of the Gulf of Mexico. Even more critical for the initial design, would be if the vessel was intended for operations in polar climates. If geographical versatility is an important attribute, and with uncertain future operating areas, we should perhaps design the vessel for the most challenging environments. However, this would have implications on the technical and commercial aspects, concerning for example dynamic positioning capabilities and the operating costs.

Operational uncertainty should also take into account what happens when things do not go as planned. For example, what happens when a system experiences failure during an operation? First, operational uncertainty has implications for the safety of the crew and the ship. Second, operational uncertainty can have far reaching consequences going beyond the performance of the vessel itself. The ship is part of a larger value chain, and disruptions in the chain due to failures may have consequences elsewhere in this value chain [11]. Design measures using flexibility and redundancy on a ship subsystem level, or on higher levels, may reduce the consequences that such disruptions have on the operations.

C. Technical aspects

Time is a key parameter in the early stage of concept vessel design, primarily due to high market competitiveness. Hence, high fidelity calculation methods for detailed design analysis, like finite element methods (FEM) and computational fluid dynamics (CFD), should be postponed to later stages when the conceptual design characteristics are defined. However, the use of lower fidelity calculation methods, based on experience data and generalized equations, introduces higher technical uncertainty in the decision-making process as well as lower accuracy. Time is not the sole characteristic of the ship design industry influencing technical uncertainties. Offshore ship design companies need to be innovative, flexible and agile, in order to keep a high competitive level in the market [12]. Such a factors lead to the development and use of innovative and unproven solutions, which will typically lead to a higher level of uncertainty.

Technical uncertainty relies on the accuracy of the design parameters during the development of a new vessel. Lightweight, speed, deck load, etc. are design parameters that evolve through the design process, with values strongly related to other design variables. On that line, the designer has to deal with technical uncertainties that will be reduced through the shipbuilding life cycle, finally disappearing when the vessel performs the sea trials.

III. APPROACHES FOR HANDLING UNCERTAINTY

This section discusses relevant approaches and methods for system modelling and decision-making that could be used for handling uncertainty relating to various technical, operational and commercial aspects.

A. Margins

The purpose of margins is to ensure at least a minimum system performance [13]. Uncontrolled use of margins, in order to ensure the validity of the results, could lead to non-competitive vessel designs. For example, excessive hull strength will increase the weight of the vessel, hence reducing the performance and increasing the costs. Vrijdag, de Jong and van Nuland [14] describe the use of margins in the calculation of the bollard pull in tugs. The uncertainty related with the final performance and the penalties related to such a parameter, require the use of margins, in order to ensure the contractual bollard pull.

B. Data science

The most basic process for handling uncertainty is the generation of information. Research could be used for providing information for quality decision making [15]. Although good research does not eliminate the uncertainty involved in decision-making completely, it can efficiently reduce uncertainty [16]. The use of historical data to develop coefficients and equations for use in early stages has been widely used in the industry [17]. The use of these conventional approaches typically does not adequately address unconventional or innovative designs, for which little statistical data exist. The introduction of data gathering devices and the evolution of Big Data analysis tools brings the possibility of using real data from existing vessels in handling and reducing uncertainty in early stages vessel design processes [18].

C. Design structure matrix (DSM) system representation

DSM can be used for modelling how change propagates through a design, thus enabling DSM as a tool for describing the design under future uncertainty. Using the sensitivity DSM [19], Kalligeros et. al. [20] study how a Floating Production, Storage and Offloading (FPSO) unit can be designed. Mapping functional requirements onto design variables, and studying how the functional requirements may change, change-sensitive design variables can be identified. By finding the largest set of design variables that are not sensitive to changes, designers can formulate a platform design that will be valid under many differing functional requirements. We can install systems represented by the design variables, to match differing functional requirements relating to the current context of the system. For this reason, sensitivity DSMs are mostly fit for handling technical aspects, even though DSMs in general have applications in project management as well.

D. Real options analysis

A common approach for handling commercial uncertainty is by incorporation of flexibility in design [21]. Designing flexible systems involves both identifying and valuing real options. For complex engineering systems this relates to "in" options, which in contrast to traditional real "on" options do not treat technology as a black box [22]. Identification of flexibility involves finding those options that are most relevant to include. Valuing flexibility with real options analysis can then be used to assessing which options should be included in a design. A real option example can be market switching in shipping [23], introducing the option to switch between wet and dry markets. The flexible ship will be able to operate in the most profitable of those markets, hence this option increases the expected lifecycle performance of the ship. However, the option also comes at a cost.

An important part of option valuation is to properly describe the uncertain variables. Uncertain variables, such as the oil price and freight rates, are usually time series modelled as stochastic processes, such as geometrical Brownian motion or mean reversion models. For complex systems, a proper real options approach will often involve assessing portfolios of real options that interact.

E. Optimization under uncertainty

Optimization as decision support involves finding the best solution out of larger set of possible alternatives. Stochastic optimization is relevant when some of the data elements are uncertain. Problems of optimization under uncertainty are characterized by the necessity of making the best decisions without knowing what their full effects will be [24]. Stochastic optimization therefore often involves making hedged decisions that are good in various scenarios. Stochastic programs with recourse are used when decisions are made before uncertainties are resolved.

In theory, defining an adequate objective function could seem like a good approach for early stage ship design. However, for several reasons, in practice this is not modus operandi. Unless the optimization problem is formulated 100 % correctly, there are great chances that the solution produced will be suboptimal or even severely wrong. Given the complexity of a typical ship design project, it is obvious that only simplifications of reality can be modelled. In such problems one should instead settle with good enough solutions, that are not necessarily optimal – *satisficing* instead of optimizing [25].

Stochastic optimization frameworks are to a little extent applied to problems within ship design. On the other hand, when it comes to handling operational uncertainty in routing and fleet size and mix problems, stochastic optimization is applied [26].

F. *Tradespace exploration and evaluation*

Tradespace exploration is an approach for efficiently exploring the design space [27], [28] attempting to settle for an optimum design. Tradespaces present every design alternative in terms of utility versus cost. When generating a tradespace, key stakeholders involved in the commercial, operational, and technical sides of a project should be represented, in order to balance the expectations. By facilitating a broad discussion between stakeholders, we achieve a common understanding of what performance to expect from a vessel. After defining the utility function and estimating costs for all possible ship design alternatives, we can quickly identify the design solutions that better fit with the performance expectations by narrowing the search to the Pareto front.

As a perspective to understand complexity in engineering systems, Rhodes and Ross [29] and Gaspar et al [30], [31] captures complexity as relating to structural, behavioral, contextual, temporal, and perceptual aspects. To handle temporal complexity, dealing with future uncertainty, we need to assess the impact that operational, technical and commercial aspects of uncertainty have on the lifecycle value of a ship. We can treat each static context as an "epoch", and sequencing "epochs" we formulate "eras" [32]. The "eras" represent possible lifecycle scenarios, and we can evaluate performance throughout the lifecycle. A tradespace exploration is presented in an epoch-era analysis framework in Fig. 2. Industrial ship design processes at Ulstein increasingly apply decision-making methodologies based on the paradigm outlined here [1], [5].

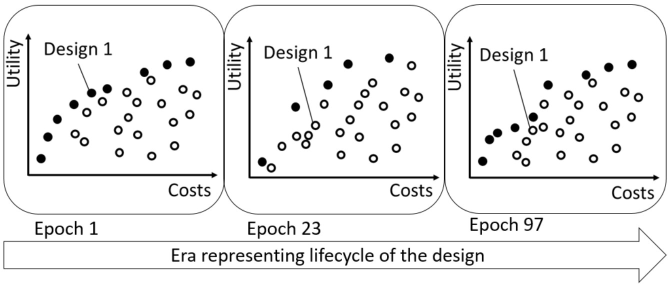

Fig. 2: Example of tradespace representation in an Epoch-Era approach.

G. *System dynamics*

System dynamics is a tool for modelling complex systems, mapping the causal relationships between decisions and external factors influencing the system [33]. In system dynamics, the causal relationships are formulated using feedback loops. System dynamics applies feedback loops not only to model how decisions influence the technical factors, but also for modelling social and economic elements of the system context.

System dynamics has been used for modelling the dynamics of shipping markets, as exemplified by the early work of Taylor [34]. He takes a macro-view of shipping markets, investigating how important events influence the industry overall. If quantitative data is available, system dynamics can help to predict the magnitude and importance of factors influencing the system. Even in situations that do not lend themselves well to quantification, visualization of these causal relationships, using rich pictures and influence diagrams, can bring valuable insight. For example, rich pictures have been used to illustrate the interactions between personnel at the shipyard and the ship designer's office [35].

IV. CONNECTING SHIP DESIGN UNCERTAINTY ASPECTS WITH SUGGESTED APPROACHES

The aim of this section is to assess the applicability of the suggested approaches in handling the three aspects of uncertainty in ship design, as illustrated in Fig. 3.

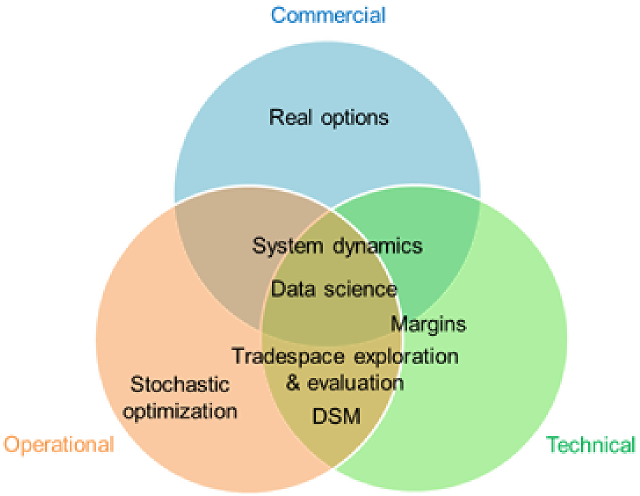

Fig. 3. Uncertainty handling approaches in a design for efficiency perspective.

Margins is and has been the most common way of handling technical uncertainty in ship design, both endogenous and exogenous types. Other discussed approaches, including data science, DSM, system dynamics and tradespace exploration and evaluation methods may provide efficient tools for designers to better understand technical system behavior, particularly for better handling endogenous technical uncertainty. Tradespace exploration and evaluation methods can also handle technical exogenous uncertainty through epoch-era analysis, by accounting for new technologies in the epoch formulation.

Regarding commercial uncertainties, the analysis of future market conditions would create a basic background for the decision-making process. System dynamics provides the decision-maker the capability to include exogenous market factors into the design process, and the application of epoch-era allows the assessment of the vessel's performance in different stages through its lifecycle. By valuation of alternative strategies for contract selection, or market switching, real options analysis has the potential to let designers take advantage of commercial upside opportunities, as well as hedging risks. System dynamics and tradespace exploration and evaluation methods may be used to reduce various aspects of uncertainty affecting the lifecycle costs, and hence the commercial performance. For example, reducing uncertainty regarding the resistance of the vessel may provide large commercial benefits.

For handling operational uncertainty, stochastic optimization has been applied for routing and scheduling purposes in an uncertain environment. It remains primarily an academic venture, although some practical cases exist [36]. In terms of handling exogenous uncertainty related to specific contractual requirements, real options analysis may be an appropriate approach. DSM supports the decision making process by mapping between design variables and performance, and vice versa, reducing uncertainty in the operating context.

An interesting remark is that technical and operational uncertainties typically relate to the risk of loss or failure. Commercial uncertainty, on the other hand, is more symmetric and may also results in a positive outcome – the market rates can for example go up or the market structure may change. However, in order to take advantage of this, the ship may have to be "prepared for" future changes – for example with the inclusion of real options. This represents an active approach to handling uncertainty, in contrast to the passive approach that is represented by for example margins.

From an industrial point of view, Ulstein has developed an Accelerated Business Development process (Ulstein ABD) to improve the quality of decision-making in early stage ship design. The Ulstein ABD process handles uncertainty by incorporating several of the approaches discussed in this paper. It consist of a structured systemic business development methodology to guide the collection and proper use of vessel case information in the development of new vessel concept designs [37]. Some internally developed tools and analyses supporting Ulstein ABD, based on the approaches discussed in this paper, are described below:

Causal mapping: The use of causal mapping, as an alternative to DSM, allows the designer to quickly assess which design parameters have influence and in which measure on the performance expectations, and at the same time on the costs of the vessel.

Fast-Track Concept Design Tool: This is an approach based on multi-variate statistics, network resources and design expertise to accelerate effective decision making in vessel concept design. It combines Base-ships, tradespace exploration, standardization and modularization of hull platforms and topside elements to identify the most effective design solution.

Multi-criteria benchmarking: Ulstein and Brett [1] introduce a multi-criteria approach for supporting the decision-making process, in order to improve the design's performance and describe "What is a better ship". This approach, based on a multi-criteria performance index, benchmarks the design alternatives with existing vessels. It allows the identification of potential improvement factors by comparing with the Pareto front of the current fleet. Ebrahimi et al. [5] presents a practical case for a subsea vessel.

V. CONCLUSIONS

This paper advocates the need of decomposing ship design uncertainty in order to reduce complexity and better understand the consequences of individual uncertainty factors. A decomposition based on a *design for efficiency* perspective seems to be a promising approach, although it potentially introduces complexity due to the interconnections between uncertainty aspects. The combination of management, financial and systems theory allows the consideration of a wider range of performance factors when handling uncertainties. The various approaches discussed in this paper enable decision makers to better account for the consequences of changes and uncertainties on a ship's lifecycle performance.

The commercial aspects of exogenous uncertainty in the offshore market, typically related to the oil price, often drive operational and technical uncertainty. In addition, technical and operational uncertainties affect the commercial performance. In the end, the vessel should be profitable from a commercial perspective. Thus, in addition to the proposed design for efficiency perspective, it would be of interest to further investigate the complexity of the system dynamics.

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